Automatic wavelength spectrometer calibration during arc-welding process

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***Abstract*- Spectroscopic analysis techniques are widely used in a variety of scientific areas. The availability of low-cost CCD spectrometers has also allowed their development in several industrial applications, like on-line analysis of arc and laser welding processes. A correct spectrometer wavelength calibration is always required, specially when changes in ambient temperature are to be found, or when the optical fiber attached to the spectrometer is replaced. This calibration procedure commonly involves the recalculation of a pixel-wavelength polynomial by means of regression techniques after having defined a new experimental setup. Besides, specific calibration lamps are needed to use some known emission lines in the regression stage. In this paper, a technique which allows a real-time, in-process automatic wavelength calibration of CCD spectrometers in arc-welding processes is presented. The key point in the automatic calibration process is the real-time identification of some particular emission lines emitted from the plasma generated during the welding process. TIG welding tests performed on stainless steel plates will show the feasibility of the proposed technique. As well as for laser welding, the automatic wavelength calibration procedure could be easily extended to some other spectroscopic techniques.**

I. INTRODUCTION

Quality assessment in both laser and arc welding processes has been an active area of research for years. Welding processes are used in several different industrial scenarios, and in some of them, like the automobile, nuclear or aerospace sectors, issues regarding quality evaluation are of great concern. However, the complexity involved in these welding processes has made it difficult to obtain a successful sensing and control system able to ensure some specific weld output parameters and the absence of weld faults.

In the case of arc welding, different approaches have been used to acquire valuable information from the welding process: measurement of the arc voltage [1], analysis of the acoustic emissions [2] or infrared vision solutions [3], among others. Spectroscopic analysis of the plasma optical spectrum has proved to be an interesting alternative, typically by means of establishing a direct relationship between the plasma electronic temperature and the quality of the weld [4,5]. When spectroscopic analysis is to be performed, CCD spectrometers are commonly selected to obtain the spectra of the elements or procedures being analyzed. However, to obtain the relationship between the CCD pixel number and wavelength, a calibration procedure must be carried out whenever the conditions of the experimental setup are modified, especially when spectral resolution is of great concern.

In this paper, a new technique which allows in-process, real-time, automatic wavelength spectrometer calibration is presented. The technique has been successfully validated with TIG welding tests on stainless steel plates. The automatic calibration method has been integrated in a real-time spectroscopic system for welding quality assessment.

II. CCD WAVELENGTH CALIBRATION PROCEDURE

Although different approaches may be considered, the relationship between the spectral wavelength and the pixel number can be expressed by means of:

$$\lambda(p) = C_0 + C_1 p + C_2 p^2 + C_3 p^3 \qquad (1)$$

where λ is the wavelength associated to pixel p, C_0 is the intercept (the wavelength corresponding to pixel 0) and C_1, C_2 and C_3 are also constants to be determined. The process of wavelength calibration involves the utilization of a calibration lamp able to generate emission lines within the range of interest of the selected spectrometer. As a precise estimation of the central wavelength of those emission lines is known, a linear regression can be performed and, therefore, C_0, C_1, C_2 and C_3 can be obtained.

Given equation (1), and considering at least four pairs of known emission line central wavelength – CCD pixel number, the unknown coefficients can be determined by trying to minimize the following expression:

$$S = \sum_{i=0}^{m} \left[\lambda(p_i) - y_i\right]^2 , \qquad (2)$$

where y_i represents the known wavelengths from the calibration lamp selected emission lines. This method is commonly referred to as *linear least squares regression*.

Considering the partial derivatives of S with respect to the coefficients, and equalling to zero, the resulting equation system for an 3[rd]-order polynomial would be given by

$$\begin{pmatrix} n & \sum_{i=1}^{n} p_i & \sum_{i=1}^{n} p_i^2 & \sum_{i=1}^{n} p_i^3 \\ \sum_{i=1}^{n} p_i & \sum_{i=1}^{n} p_i^2 & \sum_{i=1}^{n} p_i^3 & \sum_{i=1}^{n} p_i^4 \\ \sum_{i=1}^{n} p_i^2 & \sum_{i=1}^{n} p_i^3 & \sum_{i=1}^{n} p_i^4 & \sum_{i=1}^{n} p_i^5 \\ \sum_{i=1}^{n} p_i^3 & \sum_{i=1}^{n} p_i^4 & \sum_{i=1}^{n} p_i^5 & \sum_{i=1}^{n} p_i^6 \end{pmatrix} \cdot \begin{pmatrix} C_0 \\ C_1 \\ C_2 \\ C_3 \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} y_i p_i \\ \sum_{i=1}^{n} y_i p_i^2 \\ \sum_{i=1}^{n} y_i p_i^3 \end{pmatrix} \qquad (3)$$

The solution to the unknown parameters of equation (3) can be achieved by using the so-called Gauss-Jordan method [6]. The advantages of avoiding the necessity of having to perform this step periodically lie, not only on the saving of time of the operator, but also on the elimination of the costs associated to the calibration lamp. In addition, when talking about industrial processes like welding, where the sensing solutions have to be non-invasive to be effective, eluding the manual wavelength calibration process would be also an important asset.

III. Automatic Wavelength Calibration in Arc Welding Process

The common approach when using plasma spectroscopy to monitor and control weld processes is to collect the plasma light emission by means of some input optics like collimators or photodiodes. Once the plasma spectrum has been captured, some processing stages must be fulfilled to obtain the plasma electronic temperature T_e. This parameter, as it was mentioned in Section I, is known to exhibit a direct correlation with the quality of the resulting welds. The basic processing steps to calculate T_e are schematically depicted in Figure 1.

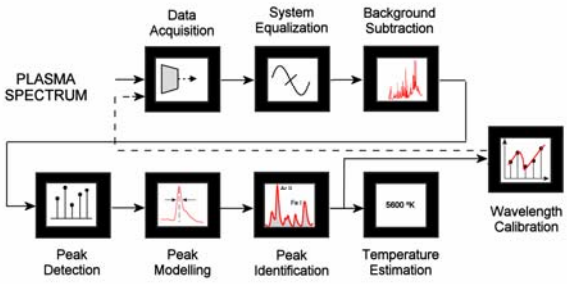

Fig. 1. Plasma spectrum processing stages with automatic wavelength calibration

When the plasma light radiation has been captured by means of the input optics, and the spectral response of the optical system (input optics, optical fiber, spectrometer) has been used to equalize the input data; a removal of the typical plasma spectrum background signal is performed by using a smoothing algorithm. The key point of the analysis lies in the identification of each selected peak, which is performed by accurately determining the central wavelength of those peaks, and then searching in a local copy of the NIST atomic spectra database [7]. With two or more emission lines from the same atomic species, within those participating in the plasma, the value of T_e can be established. Nevertheless, in order to perform the wavelength automatic calibration of the spectrometer, this step is not necessary. Once several emission lines have been successfully identified, their central wavelengths will be used in equation (3) to calculate the unknown coefficients.

The plasma processing system depicted in Figure 1 has been demonstrated to be valid for real-time operation [8]. Consequently, starting with some reference values, like the coefficients provided by the spectrometer manufacturer, the proposed system will find, for each single plasma spectrum processed, a new set of calibration coefficients according to the spectral lines selected for the calibration process. By establishing an error threshold or a maximum number of iterations, the automatic calibration can be deactivated, as its processing will be of no use during a whole welding procedure.

IV. Experimental Setup and Results

As it was mentioned before, the proposed technique has been tested within an arc welding quality assurance system. The experimental setup used in the laboratory to perform TIG welds and to collect and process the plasma spectral information is schematically depicted in Figure 2.

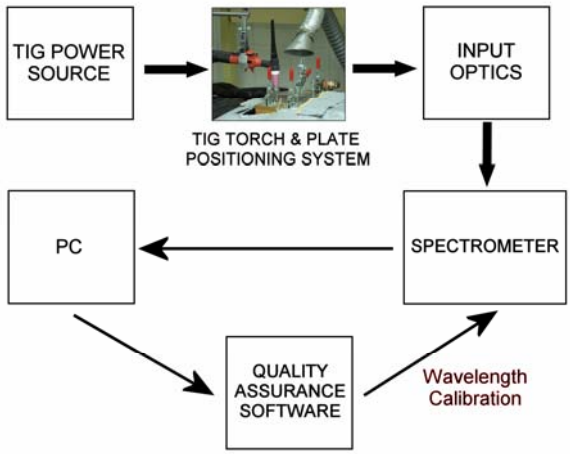

Fig. 2. Experimental system setup

In our system, the TIG torch is fixed, while the movement of the plates is controlled by means of a high-precision positioning system, formed by the controller (Newport MM4005) and two linear stages (Newport MTM100PP1), with a resolution of 1μm in both axes. AISI-304 stainless steel plates have been used as specimens, with a tungsten electrode and argon as shielding gas. Once the welding process has started, and the arc between the electrode and the plate is formed, the axial plasma generated emits light which is collected with the input optics depicted in Figure 3.

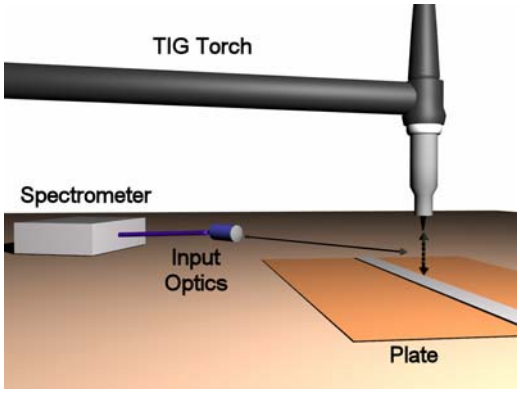

Fig. 3. Input optics arrangement.

A collimator aimed at the center of the plasma axis collects the light, which by means of an optical fiber (2

meters length) is transported to the spectrometer (Ocean Optics USB2000). The CCD of the spectrometer (Sony ILX511 linear silicon CCD array) has 2048 pixels, a spectral resolution of 0.3 nm, and its spectral range is defined from 194 to 535 nm. In this spectral region several emission lines from the plasma generated during the TIG welding process can be observed. In Figure 4 a typical plasma spectrum is presented.

The polynomial coefficients of equation (1) offered by the manufacturer, relating wavelength and pixel number, are presented in Table 1. The first step performed to improve the accuracy of the calibration polynomial was to calculate a new set of coefficients by using the Ocean Optics CAL2000 calibration lamp, and then performing a linear regression after having fitted all the emission lines considered to a Gaussian lineshape. In addition, the pixel number associated to each peak maximum was taken, not as an integer, but considering some representative decimal digits. In Table 1 it can be seen that the resulting quadratic mean error is one order of magnitude better than the one obtained with the original polynomial. The error was measured as the difference between the known value for each CAL2000 peak and the wavelength value provided by the polynomials.

A detailed description of the error associated to each individual peak considered in the regression process is displayed in Table 2. The distance in nm^2 between the known peak wavelength center provided by the CAL2000 manufacturer and both polynomials is always smaller with the fitted polynomial, with exception of the Hg emission line located at 365.015 nm.

Polynomial coefficients and mean error

Manufacturer Coefficients

C_0	C_1	C_2	C_3	Mean Error (nm^2)
193.953841	0.189284	-1.110E-05	0	0.049758

Coefficients after Gaussian Fitting

C_0	C_1	C_2	C_3	Mean Error (nm^2)
194.947413	0.186984	-9.0745E-06	-6.630E-10	0.002790

Table 1. Manufacturer and fitted calibration polynomials

CAL2000 peaks error after regression

CAL2000 peaks considered

Peak Wavelength (nm)	Manufacturer Polynomial Error (nm^2)	Fitted Polynomial Error (nm^2)
253.652	0.2037611	4.620E-05
296.728	0.0362787	0.0011565
302.15	0.0211537	0.0035600
313.155	0.0800434	0.0124904
365.015	0.0006657	0.0017472
404.656	0.0008985	0.0005026
435.833	0.0055046	3.026E-05

Table 2. CAL2000 polynomials peak error

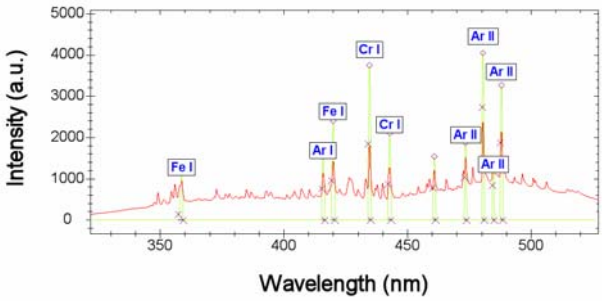

Fig. 4. TIG plasma spectrum

Automatic calibration process

Weld Test 1

Number of Peaks	Iterations (spectral samples)	Mean Error (nm)
0	0	0.054234
10	10-20	0.045999
20	0-10	0.058072
20	0-15	0.037211
20	10-30	0.037554
14	10-20	0.041569
16	10-20	0.037117
18	10-20	0.038023

Weld Test 2

0	0	0.049647
20	10-20	0.039866
20	0-10	0.048247
15	10-20	0.043649
10	10-20	0.038712

Table 3. Automatic calibration polynomial peak errors.

In the case of the automatic calibration process, the calculation of the central peak wavelength is not performed by means of peak fitting, as these techniques are commonly iterative and, therefore, computationally inefficient. A sub-pixel algorithm, the Linear Phase Operator (LPO), has been chosen to precisely estimate the pixel number attached to the center of each processed emission line [9].

Several tests were performed to check the validity of the proposed technique. The main parameters in the automatic calibration process are the number of peaks considered in the linear regression and the number of iterations (spectral captures) used to find the optimal polynomial coefficients. In Table 3 the results for two different weld tests are presented. An argon flow rate of 12 L/min and welding currents of 20 and 52 A were used for tests 1 and 2 respectively.

When no automatic calibration is used, the polynomial employed to transform from pixel number to wavelength is the one obtained by means of Gaussian-fitting (Table 1). The error is in this case calculated as the absolute value of the

difference between the identified emission lines and the result provided by the polynomial determined with the automatic calibration process. It can be seen that in the Test 2 the worst result is the one obtained when the automatic calibration process is not activated. With the first test there is an exception, as a greater error is achieved when 20 peaks and 10 iterations (from captures 0 to 10) are the calibration parameters. The explanation to this can be found in the high instability associated to the beginning of the welding process. Therefore, the first captured plasma spectra are also unstable, and different emission lines are to be found in consecutive captures. Consequently, it has been found better not to use the first captured spectra. The best result in both cases has been reached when using the spectra from captures 10 to 20, using 16 peaks in test 1 and 10 peaks in test 2. Although the differences in the error value are small when varying the number of peaks employed in the calibration process, it must be noted that the use of more peaks will not always produce a better result, as some emission lines will be more suitable than others to be used in the linear regression.

V. Conclusions

A new technique that allows an automatic wavelength calibration of CCD spectrometers in arc welding spectroscopic sensor systems has been presented. The technique, which could also be used in other spectrometer applications, avoids the use of calibration lamps, as well as the waste of time associated to the wavelength calibration procedure which must carried out periodically. Within an arc welding quality assurance system, the technique has been validated, using a real-time plasma emission line identification technique. Once a set of emission lines has been identified, a linear regression is performed to obtain the new polynomial coefficients of the function which relates the CCD pixel numbers with the resulting wavelengths. The proposed technique has been successfully checked with several TIG welding tests on stainless-steel plates.

Acknowledgements

This work has been co-supported by the Spanish TEC'2004-05936-C02-02 and TEC'2005-08218-C02-02 projects.

Authors also want to thank J.J. Valdiande for his valuable collaboration in the development of the TIG welding tests.

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